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<b>14. ABSTRACT</b> Generation of artificial light in the sky by means of high-power radio waves interacting with the ionospheric plasma has been envisaged since the early days of radio exploration of the upper atmosphere, with proposed applications ranging from regional night-time street lighting to atmospheric measurements. Weak optical emissions have been produced for decades in such ionospheric "heating" experiments, where they serve as key indicators of electron acceleration, thermal heating, and other effects of incompletely understood wave-particle interactions in the plasma under conditions difficult to replicate in the laboratory. The extremely low intensities produced previously have, however, required sensitive instrumentation for detection, preventing applications beyond scientific research. Here we report observations of radio-induced optical emissions bright enough to be seen by the naked eye, and produced not in the quiet midlatitude ionosphere, but in the midst of a pulsating natural aurora. This may open the door to visual applications of ionospheric heating technology or provide a way to probe the dynamics of the natural aurora and magnetosphere.				
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# nature

## **Creation of visible artificial optical emissions in the aurora by high-power radio waves**

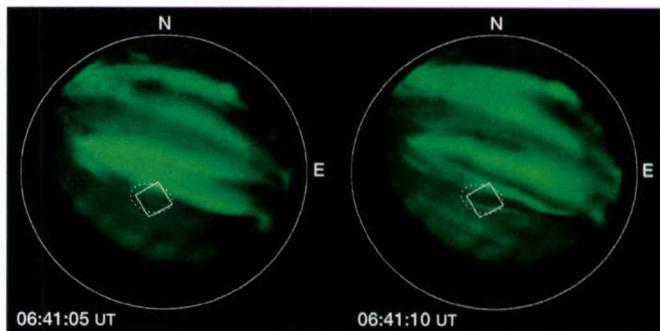
Todd. R. Pedersen<sup>1</sup> & Elizabeth A. Gerken<sup>2</sup>

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ionospheric 'heating' experiments, where they serve as key indicators of electron acceleration, thermal heating, and other effects of incompletely understood wave-particle interactions in the plasma under conditions difficult to replicate in the laboratory<sup>2</sup>. The extremely low intensities produced previously have, however, required sensitive instrumentation for detection, preventing applications beyond scientific research. Here we report observations of radio-induced optical emissions bright enough to be seen by the naked eye, and produced not in the quiet mid-latitude ionosphere, but in the midst of a pulsating natural aurora. This may open the door to visual applications of ionospheric heating technology or provide a way to probe the dynamics of the natural aurora and magnetosphere.

The most readily observed emissions produced in ionospheric heating are the 'forbidden' red and green lines from atomic oxygen at 630.0 and 557.7 nm, both common components of the natural aurora and airglow<sup>3</sup>. In almost all past experiments, artificial emissions have been produced by the interaction of radio waves with the ionospheric F region, the long-lived primary ionospheric layer composed of atomic ions at an altitude of several hundred kilometres<sup>4</sup>. Only rarely have optical effects been reported from the ionospheric E region<sup>5</sup>, an ephemeral layer created from occasional meteoric ions or continuous solar illumination or auroral precipitation near an altitude of 100 km (ref. 4), where increased collisions with neutral molecules alter the behaviour of the plasma, and the proximity to the transmitter provides a large inverse-square increase in power density<sup>5</sup>. Emission intensities achieved previously have typically ranged up to several hundred Rayleighs ( $1 R = 10^6 \text{ photons cm}^{-2} \text{ s}^{-1}$  integrated along a line of sight) for the more easily excited red line and tens of Rayleighs for the higher-energy green line. In all cases, intensities have remained far below



**Figure 1** A pair of all-sky images taken 5 s apart showing the dynamic natural background aurora pulsating in long bands over most of the sky. These images were taken at 557.7 nm during the minute of 06:41 UT on 10 March 2004, when the HAARP transmitter was operating in O-mode polarization at a frequency of 5.95 MHz, providing 95 MW effective radiated power (ERP) directed at the magnetic zenith (azimuth 204°, elevation 75°). The half-power contour of the beam, represented by the dotted oval, enclosed a region approximately 15° by 21°, or 26 km by 37 km at an altitude of 100 km. The solid circle indicates the horizon, and the field of view of the higher-resolution imager is indicated by a white square. The pulsating auroral bands shown here were observed near 20:00 magnetic local time as part of the declining phase of an auroral event that had already persisted for several hours and reached more than 400 nT at its peak. The  $K_p$  planetary magnetic activity index was 6 for the three-hour periods before and after 6 UT. Auroral precipitation during this hour produced E layers ranging from ~4–6 MHz in critical frequency:  $(2.0\text{--}4.5) \times 10^{11} \text{ electrons m}^{-3}$ . The E layer at this time was centred at an altitude of about 110 km with a peak frequency of ~6.0 MHz and a half-thickness of 10–15 km. The nominal reflection altitude at the 5.95-MHz transmitter frequency was 109 km. Note that the time constant for changes in the E-region density is about 10 s (ref. 9), compared to the several minutes required to collect an ionogram, so nominal parameters cannot be expected accurately to represent instantaneous conditions in this highly dynamic environment.

## Creation of visible artificial optical emissions in the aurora by high-power radio waves

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Generation of artificial light in the sky by means of high-power radio waves interacting with the ionospheric plasma has been envisaged since the early days of radio exploration of the upper atmosphere, with proposed applications ranging from regional night-time street lighting to atmospheric measurements<sup>1</sup>. Weak optical emissions have been produced for decades in such

the threshold for detection by the human eye, which is given as 20 kR at 630 nm (ref. 2) towards the red end of the visible wavelength range, and 1 kR for 558 nm (ref. 6) near the peak sensitivity of the eye.

We recently produced dramatically stronger artificial optical emissions bright enough to be visible to the naked eye in an experiment targeting the ionospheric E layer created by the natural aurora. The experiment was conducted on 10 March 2004, between ~6–7 UT, using the 960-kW transmitter array at the High Frequency Active Auroral Research Program (HAARP) facility near Gakona, Alaska ( $62.4^\circ$  N,  $145.15^\circ$  W). The HAARP transmitter was run in a 15-s cycle alternating between 7.5 s of full power and 7.5 s off. Four filtered optical imaging systems ranging from all-sky to telescopic were operated in synchronization with the transmitter on and off intervals. Background conditions during the experiment period were characterized by aurora pulsating with apparent periods of ~10 s in longitudinal bands running in the magnetic east–west direction over most of the sky, including the region within the transmitter beam (Fig. 1). The auroral precipitation created a blanketing E layer near an altitude of 100 km with critical frequencies ranging from 4–6 MHz.

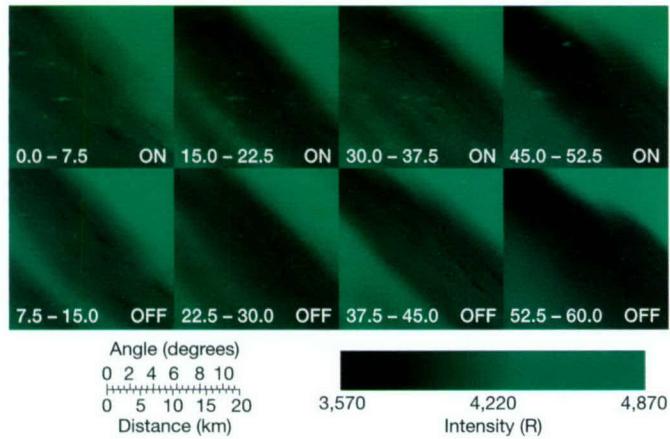
For a period of approximately 10 min between about 06:40 and 06:50, a number of small speckles of enhanced green emission were observed with the HAARP telescope wide-field camera, which provided high-resolution images of the region within the transmitter beam near magnetic zenith (Fig. 2). The speckles were present only during the image frames when the transmitter was on and were absent from exposures taken during the off periods. There is

evidence of dynamic pulsations in the background aurora within this narrower field of view as well, such as the auroral bands that appear and disappear in the lower left corner of the images. The largest speckles are approximately one degree across.

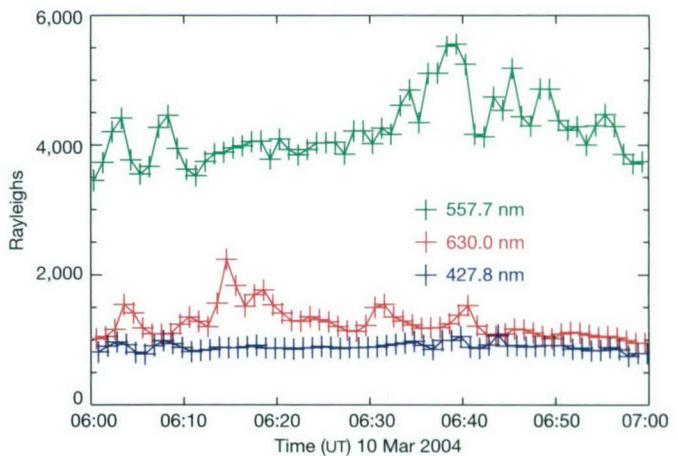
Within a given frame the speckles appear to be randomly distributed, but upon closer examination of successive ‘on’ frames, some of the speckles often appear to be correlated with but displaced from those seen in the previous ‘on’ period. This suggests that some speckle features are in motion but may still retain coherence across multiple on–off cycles of the transmitter.

Calibrated average intensities for the background aurora within the transmitter beam were obtained from another imager, which made measurements at several different wavelengths once each minute (Fig. 3). In spite of the rapid pulsations in narrow bands and on 10-s timescales, the average auroral brightness at 557.7 nm remained near 4 kR, with an increase to ~5 kR near the time the speckles were observed. This intensity calibration, applied to the high-resolution data in Fig. 2, indicates that the brightest speckles were approximately 4 kR in total intensity, well above the threshold for visibility and 1 kR or more above the darker auroral regions.

Given the unprecedented brightness of the speckles, we carried out a number of tests to rule out potential artefacts, including: repeating the transmission pattern at a different time to rule out radio-frequency (r.f.) interference with the camera electronics, verifying from radar records that no aircraft were in the area, and measuring the periods of white-light sources such as nearby communications towers and airport beacons. We attempted to reproduce the results whenever an aurora moved into range, but auroral events later in the experiment window never produced E layers of sufficient density to support significant transmissions at



**Figure 2** Images from the HAARP telescope wide field camera showing speckle-like artificial optical emissions superimposed on the background aurora only during frames when the transmitter was on. These data were taken at 557.7 nm during the minute of 06:41 UT on 10 March 2004. Frames taken during the 7.5 s the HAARP transmitter was turned on are in the top row with ‘off’ images along the bottom row. The camera was pointed at the magnetic zenith and covered a field of view of about  $12^\circ$  across, corresponding to a distance of about 20 km at an altitude of 100 km of the auroral E layer. Each image was integrated for just over 7 s so that with the data readout time the system would start each exposure at the beginning of each 7.5-s on or off period, indicated at lower left. True zenith is towards upper right and west is towards lower right. The speckles are visible in the upper row as bright spots much bigger than the stars and noise pixels. The larger speckles are approximately 30 pixels, or one degree, across, corresponding to a true size of about 1.75 km at the assumed 100-km altitude of the emission. The elongated shape and apparent displacement of many of the speckles are consistent with motion of the features of the order of several hundred metres per second of exposure time. Some frames, including those shown here, show small darker bands in the background suggestive of black aurora<sup>10</sup>, but as speckles are present in other frames lacking any apparent black aurora there does not appear to be any direct correlation.



**Figure 3** Calibrated measurements from the HAARP imager showing the intensities of various auroral emissions including the oxygen green line, which was well above the threshold for detection by the naked eye during the experiment. The plot covers the period from 6–7 UT on 10 March 2004. The HAARP imager observed an approximately  $16^\circ$  field of view centred on the magnetic zenith and took images at each wavelength once per minute. The red line at 630.0 nm results from the  ${}^1D$  state of neutral atomic oxygen (1.96-eV excitation energy), and is sensitive to lower-energy auroral particles at higher altitudes, while the green line at 557.7 nm arises from the  ${}^1S$  state (4.17 eV) and corresponds to more energetic particles and somewhat lower altitudes<sup>3</sup>. The 427.8-nm emissions from the first negative band of  $N_2^+$  are an indicator of the ionization rate in the E layer<sup>11</sup>. At the ~100-km altitude of the E layer, more frequent collisions between neutral molecules deactivate or ‘quench’ the long-lived  ${}^1D$  state before it can produce the red line (effective lifetime of the order of 1 min)<sup>2</sup>, leaving only the green line with its shorter lifetime of about 0.7 s (ref. 3) in artificial emissions from the E region<sup>5</sup>.

the original frequency again. More detailed analysis of the data revealed additional weak speckles earlier in the original 6-UT hour, at about 06:20 UT, when the transmitter was operated at a lower frequency (and lower effective power), and some of the brightest speckles were also identified in data from one of the other lower-resolution camera systems operated from a separate building, eliminating any doubt that the speckles represent actual light from the sky.

Although visible levels of artificial optical emissions have not been reported previously, there have been other attempts made to stimulate the auroral E layer with radio waves. A similar experiment that used low-light television cameras and a 2-s on-off cycle but different polarization reported an estimated modulation of less than 10 R, interpreted as radio-induced decreases in the green line emission<sup>7</sup>. Large-scale structural changes in the overhead aurora have been reported in conjunction with E-layer heating<sup>8</sup>, but the extremely small number of cases and the close similarity of the observed effects to naturally occurring processes make it difficult to assess the true influence of the radio waves on the auroral events. In contrast, the recent HAARP observations demonstrate clear on-off control of the speckles over 50 or more complete cycles.

Potential sources of the observed bright speckles fall into two categories: production in the local E-region ionosphere by the transmitter beam, or indirect creation by modification of the auroral particle precipitation, which then produces the optical speckles in the same way as the background aurora. If the speckles are locally generated, the role of the natural aurora would probably be limited to creation of the E layer for the radio waves to interact with, and it might be possible to generate similar phenomena in non-auroral E layers independent of any specific on-off cycling, a potentially desirable condition for creation of visible artificial light. If, on the other hand, the speckles result from modification of the auroral particle population, perhaps through perturbations to currents flowing in the E layer or a wave resonance, we expect that the specific frequency of the on-off cycling relative to the natural pulsation frequencies might be a critical parameter, and experiments of this type could potentially become a new tool for exploration of time-dependent processes in the aurora and magnetosphere. □

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